

IN MEDIUM EFFECTS ON THE ϕ MESON

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Abstract

The temperature dependence of the ϕ meson mass and its decay width ($\phi \rightarrow K\bar{K}$) have been studied from an effective non-linear chiral Lagrangian in $SU(3)$. Effective mass has been obtained from the pole position of the full propagator. The width has also been calculated. It has been found that the mass decreases with temperature very slowly whereas the decay width increases quite sharply. Possible consequence on the QGP signals is discussed.

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The expected formation of a new phase of strongly interacting matter called Quark Gluon Plasma (QGP)[1], the restoration of the spontaneously broken chiral symmetry [2] and other such tantalizing possibilities make the study of hot and dense hadronic matter a vibrant area of research. QGP, if it is formed, exists only for a fraction of the total evolution time. So to look for the signals of QGP is both an interesting as well as challenging field of research. This is particularly so because one has to disentangle the signals coming from the hadronic sector. For example, it is believed that dileptons and photons are good signals of QGP [3]. The interactions of these particles with the surroundings are electromagnetic in nature. Hence, they are affected the least by the final state interactions, enabling them to bring out information from the core of the plasma. However these particles are also produced in hadronic processes and one has to subtract the hadronic contribution to get the information about QGP. Therefore the study of effective meson masses [4] and decay widths at finite temperature is of high current interest; in addition to having bearing on the possible signatures of the putative phase transition, they may also provide important information about the state of the hot and dense hadronic matter formed in ultrarelativistic heavy ion collisions.

From the hadronic sector dileptons may be produced by reactions like $\pi^+\pi^- \rightarrow \rho \rightarrow \mu^+\mu^-$ and/or $K\bar{K} \rightarrow \phi \rightarrow \mu^+\mu^-$. Other channels (like decays and binary reactions of various hadrons) may also be important, as argued by Gale and Lichard [5]. They are however important for $M > 1.5\text{GeV}$. The $\pi^+\pi^-$ annihilation is very well studied at finite temperature. The study of $K\bar{K}$ annihilation is interesting in the sense that the mass of ϕ meson is very close to twice the K meson mass. Hence, even a small change in the ϕ meson or K meson mass may have a strong effect on this process. If the ϕ mass falls below twice the K mass then no ϕ peak will be observed in the dilepton spectra. Asakawa and Ko [6] and Ko and Siebert [7] have used this possibility to propose a new signal for the measurement of the transition temperature, namely the occurrence of a secondary ϕ peak. In this letter, we examine

critically the validity of these premises.

Since hadrons cannot yet be described by QCD, due to our limited knowledge of its non-perturbative features, we have to depend on models. Hence, all the calculations so far are model dependent and the results vary widely from model to model [4]. Ko and collaborators [6, 7] based their conclusions on the temperature dependence of the ϕ mass calculated from the QCD sum rule. Here we will use the nonlinear σ (NLS) model [8, 9], which reproduces the low energy structure of QCD quite successfully. This is a purely hadronic model where confinement does not play any role. In our opinion, this provides a great advantage over the Nambu-Jona-Lasinio model or other effective quark models. In a previous work, the temperature dependence of K mass has been studied [10] in NLS with broken $SU(3)_V$. Here we will look at the temperature dependence of the ϕ meson mass and its decay width within the same level of approximations as in [10]. Since we are primarily interested in studying the $\phi \rightarrow K\bar{K}$, the importance of $SU(3)$ in this context cannot obviously be stressed too strongly.

There are two popular and equivalent approaches to the chiral effective model; the Hidden Gauge Symmetry Approach (HGSA) [9] and the Massive Yang Mills Approach (MYMA) [8]. In this paper we will follow the HGSA. In this approach the vector mesons are incorporated as the dynamical gauge bosons of the hidden local symmetry contrary to the MYMA where the masses of the vector mesons are put in by hand. The HGSA Lagrangian, at the lowest order, can be written as a linear combination $\mathcal{L}_A + a\mathcal{L}_V$, a being an arbitrary parameter which is fixed from the condition of reproducing the Vector Meson Dominance (VMD). This condition leads to $a = 2$. The Lagrangian in presence of $SU(3)_V$ breaking term is given by [10],

$$\begin{aligned}\mathcal{L}_A + \Delta\mathcal{L}_A &= -\frac{1}{8}f_\pi^2 \text{Tr}[(D_\mu \xi_L \cdot \xi_L^\dagger - D_\mu \xi_R \cdot \xi_R^\dagger)^2 [1 + (\xi_L \epsilon_A \xi_R^\dagger + \xi_R \epsilon_A \xi_L^\dagger)]] \\ \mathcal{L}_V + \Delta\mathcal{L}_V &= -\frac{1}{8}f_\pi^2 \text{Tr}[(D_\mu \xi_L \cdot \xi_L^\dagger + D_\mu \xi_R \cdot \xi_R^\dagger)^2 [1 + (\xi_L \epsilon_V \xi_R^\dagger + \xi_R \epsilon_V \xi_L^\dagger)]]\end{aligned}\quad (1)$$

The explanation of different terms can be obtained in ref. [10]. The QCD anomaly has been incorporated via the Wess-Zumino term. The parameters have been fitted with the experimental values of the ϕ mass and the $\phi \rightarrow K\bar{K}$ decay width at zero temperature.

In the effective Lagrangian approach at zero temperature, it is assumed that the properties of the system are describable at the tree level, where the masses and the coupling constants are to be regarded as the physical ones. Loop diagrams, which are neglected here, produce only renormalization effects on them.

The calculation of effective mass follows the usual principle; Dyson's equation relates the free and the full propagators as

$$D(p) = D_0(p) + D_0(p)\Pi D(p) \quad (2)$$

where D_0 is the free propagator and D is the full propagator. The effect of interaction is embedded in the polarisation function Π . The temperature dependent polarisation has a real and an imaginary part. The real part contributes to the mass of the corresponding meson, while the imaginary part determines the decay width. Hence a self consistent solution of the equation

$$\omega^2 - m_\phi^2 - \text{Re}[\Pi_\phi(\omega, |\mathbf{k}| \rightarrow 0)]|_{\mathbf{k}_0=\mathbf{m}_\phi^*} = 0 \quad (3)$$

gives the temperature dependence of ϕ meson mass. In eq.(3) $\omega = \sqrt{|\mathbf{k}|^2 + m_\phi^{*2}}$ is the effective energy and m_ϕ^* is the effective mass of the ϕ meson. We have calculated the self energy in the one loop approximation with $K\bar{K}$ and $\rho\pi$ loop. Diagrams with heavy vector mesons in both the internal lines have been neglected as they will be Boltzman suppressed at finite temperature. For the sake of brevity, we have not shown the calculation of the self energy; these details may be obtained from ref.[4].

The ϕ pole mass as a function of temperature has been plotted in Fig. [1]. The thermal decay width ($\phi \rightarrow K\bar{K}$) has been plotted in Fig. [2]. It can be readily seen

from Fig. [1] that the mass decreases very slowly with temperature. This result has an excellent agreement with the experimental data from the AGS [11] which have become available rather recently. For the most central collisions ($T = 150\text{MeV}$), the ϕ -meson mass is found to decrease to about $1016\text{MeV} - 1017\text{MeV}$ (depending on where the p_T cut has been applied). At that temperature our result gives a value of 1016MeV . In ref. [6], the temperature dependence of ϕ mass has been calculated using the QCD sum rule. It has been reported there that the mass decreases with temperature and goes below twice K meson mass above $T = 150\text{MeV}$ which will make the $\phi \rightarrow K\bar{K}$ process forbidden [6]. But, the validity of QCD sum rule, which is based on Operator Product Expansion (OPE), is questionable at such a high temperature. According to ref.[12], QCD sum rule calculation is valid only upto 100MeV *i.e.*, when the parameter $\epsilon = T^2/6f_\pi^2$ is small. Furthermore, the QCD sum rule is not a pure hadronic picture and the relation with the hadrons is built in through the *ansatz* of parton-hadron duality. Moreover, these results fail to reproduce the experimental conclusion, even qualitatively, that the change in ϕ -meson mass should be small due to in medium effects [11]. Even more importantly, Ko and collaborators ignored the temperature dependence of the K mass entirely. In our calculation we find that ϕ meson mass always remains above the two kaon threshold; as a result, the effect of $\phi \rightarrow K\bar{K}$ decay width will be important.

As seen from Fig. [2], the decay width of the ϕ -meson increases with temperature quite sharply. In fact this result has a strong dependence on the temperature dependence of the ϕ and K -meson masses. The decay width increases from 3.7MeV (at zero temperature) to about 21MeV . In ref. [7], the decay width becomes zero at about temperature 150MeV . Our calculations show that this is entirely due to the neglect of the temperature dependence of kaon mass. The small decrease of kaon mass leads to an increase in the decay width of ϕ meson, even if the ϕ mass decreases. This is the first time that the ϕ and K meson masses have been calculated self consistently from a full $SU(3)$ chiral effective Lagrangian. Our result shows that this self

consistency is strongly required to determine the in-medium effects on the ϕ meson.

The above results have a strong bearing on the QGP diagnostics. One must immediately conclude that a primary ϕ -peak can indeed be observed in the dilepton spectrum from the hadronic sector. Obviously, the secondary peak expected from the collisional broadening of the ϕ -width [7] would be overshadowed by the primary peak. The mass shift as found in the current data is in excellent agreement with the theoretical prediction of our model.

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FIGURE CAPTIONS:

Figure 1: Temperature dependence of the ϕ mass.

Figure 2: Temperature dependence of the ϕ decay width.

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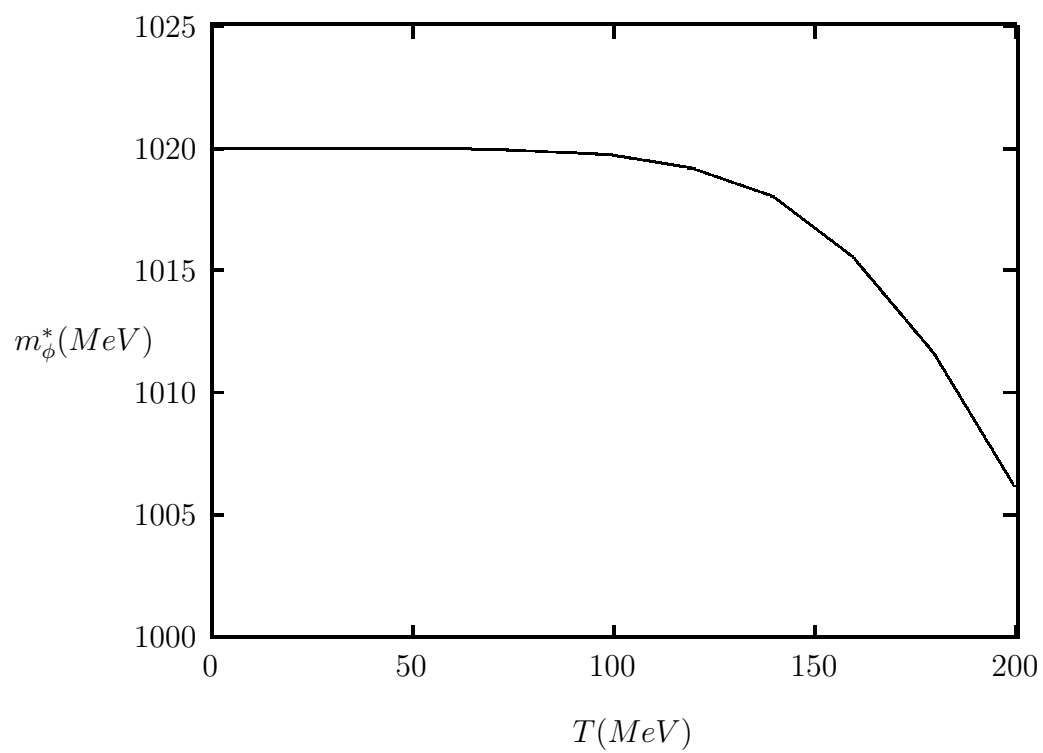


Figure 1

